IGM85-205-214
CNRC 24396

MODEL FOR THE PREDICTION OF YIELD STRESS AND RECRYSTALLIZATION ANOMALIES OF COLD ROLLED ALUMINIUM KILLED STEEL SHEETS

R. Thibau, J. Masounave,
Industrial Materials Research Institute
National Research Council Canada
75, Blvd. de Mortagne
Boucherville, Québec, Canada, J4B 6Y4

R. Decelles and L. Piperni
Sidbec Dosco Contrecoeur
C.P. 1000, Contrecoeur, Québec J0L 1C0

ABSTRACT

The formability of cold ..led low-carbon aluminium killed steel sheets depends on the recrystallization behaviour during batch annealing. For a .04% Al steel and 40% cold reduction, the resulting high yield stresses are explained by a two stage recrystallization behaviour. A simple model is proposed to predict the yield stress and recrystallization anomalies using mainly the Al content of the steel, the cold reduction percentage and a thermal parameter characterizing the annealing treatment.

INTRODUCTION

The mechanical properties of cold rolled aluminium killed low-carbon steel sheets are related to chemical compositions and thermomechanical processing variables (1). A recurrent problem for the steel industry is to be able to predict with confidence the mechanical properties at the critical location, i.e., the cold spot, of the coil after batch annealing. The main variables considered in this project are the carbon, aluminium and nitrogen contents, the coiling temperature, the cold reduction percentage and various annealing parameters, such as holding time or temperature. The annealed steel was caracterized by the yield strength (Sy), measured by a tensile test.

It is now well recognized that AlN precipitates interfere with restauration, primary recrystallization and grain growth (2). The presence of AlN particles or clusters can delay the formation of undesirable (100) nuclei, allowing the formation of texture characterized by stronger levels of (111) orientation (1,3,4).

Some authors (5,6,7,8) observed a complex recrystallization behaviour characterized by a double drop in hardness values. The intermediate stabilization was interpreted as a complete interruption of recrystallization (8). Since abnormally high yield stresses are a cause for the rejection of a coil, it is important to predict abnormal recrystallization behaviour. We are proposing a model completed by the Hillert-Zener theory of grain growth with second phase particles. This model helps to calculate the variations of mechanical properties from coil to coil and along the length of the sheet within a coil.

EXPERIMENTAL DATA

Hot rolled sheet samples, from continuous cast slabs, were cold rolled on an experimental rolling mill to 40 and 70% reductions. The composition and the coiling temperatures of the samples are shown in table 1. The tensile samples, machined according to ASTM E517 standard, were annealed under a purified argon atmosphere using a programmable furnace following industrial single stack batch annealing temperature profiles. This way, standard commercial and deep drawing sheet qualities were simulated. The tensile tests were performed at a constant deformation rate of $1.1.10^{-3}$ sec^{-1}. The mechanical values reported are calculated using the standard formula,

$$Sy = 1/4\ (S_L+S_T+2S_D) \qquad \text{(equ.1)}$$

where Sy is the yield stress and L, T, D represent longitudinal, transversal and diagonal directions.

Steel	01	02	03	04	05	06	07	08
Tb, °C	695	570	700	570	675	540	700	550
C, %	.09		.06		.08		.07	
Al*, %	.063		.059		.042		.038	
N, ppm	81		50		70		64	

* Total Al

Table 1: Composition and coiling temperature of the samples.

RESULTS

Of all the tensile results obtained, only the yield stress values are presented in this paper. The yield stresses are plotted versus a thermal parameter, P_Q (K^{-1}), equivalent to the parameter calculated by Hénin and Brun (10). The value of P_Q was computed from each temperature profile used. The expression for P_Q is:

$$P_Q = \frac{-10^4 xR}{Q} \text{Log}_e \left[\int_{t_1}^{t_2} \exp\left(\frac{-Q}{RT}\right)dt\right] \qquad \text{(equ.2)}$$

Where:

t = time, hours and R = 1.989 cal $mole^{-1}$.
T = temperature, K and Q = activation energy = 60 kcal $mole^{-1}$.

t1 and t2 are defined by the portion of the thermal cycle where T>823K. Results for low coiling temperatures (Tb=560°C) are presented in Fig.1 and 2; for high coiling temperatures (Tb=700°C) the results are shown in Fig.3 and 4.

The following four observations can be made:

1. Steels with Al=.04%, R=40% and Tb=560°C or 700°C: the yield stress is notably higher for $P_Q > 10.5$ (Fig. 1 and 3).

2. Tb=560°C, R=70%: a .03% increase in carbon content produces an increase of the yield stress of approximately 20 MPa (3 ksi), (Fig.2).

3. Tb=700°C: the thermal influence on the yield stress as given by the slope, $\Delta Sy/\Delta P_Q$, is higher for R=70% (Fig.4) than for R=40% (Fig.3).

4. Tb=700°C: the yield stress for higher carbon levels (.09%) is 42 MPa (6 ksi) higher than for lower carbon levels (.06%) (Fig.3 and 4).

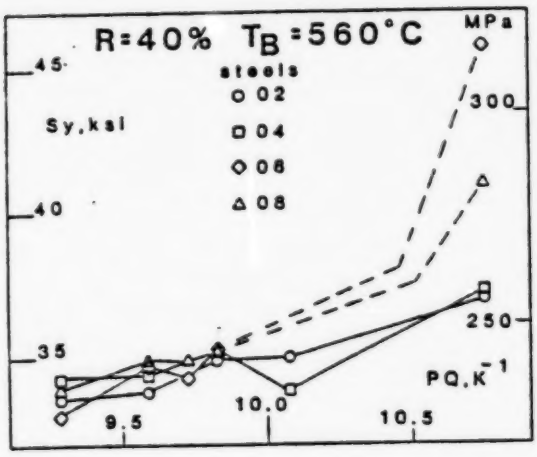

Fig. 1 Yield stress, Sy, vs P_Q for Tb=560°C, R=40%

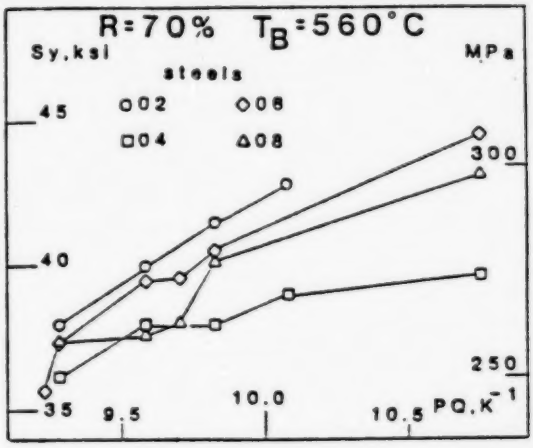

Fig. 2 Yield stress Sy, vs P_Q for Tb=560°C, R=70%

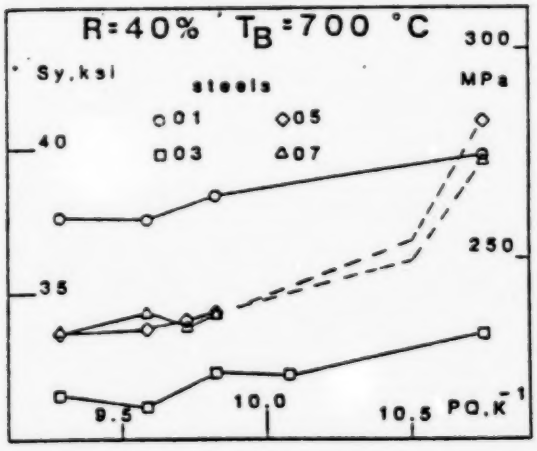

Fig. 3 Yield stress, Sy vs P_Q for Tb=700°C, R=40%

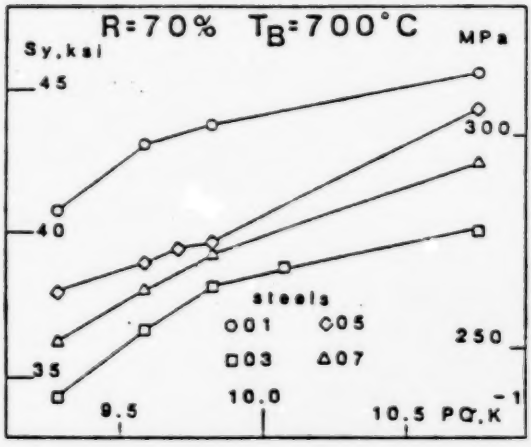

Fig. 4 Yield stress, Sy vs P_Q for Tb=700°C, R=70%

INTERPRETATION OF THE RESULTS

Following Hillert and Zener theories on grain growth and grain boundary pinning, the velocity of a grain boundary, dD/dt, depends on the grain diameter, D, and the grain size distribution characterized by a critical diameter which is usually taken equal to the average grain size, Dm. The velocity is given by:

$$dD/dt = K(1/Dm - 1/D \pm z/2\alpha) \qquad \text{(equ.3)}$$

where: $\alpha=1/2(9)$ and z is the Zener drag term given by $z=3f/4r$ (equ. 4) in which f is the precipitated volume fraction for a homogeneous precipitation and r the mean particle radius.

In the case of a grain boundary precipitation, the apparent value of f is much larger and so is the drag effect. As the growth driving force as well as the particle drag effect are similar with sub-grains, equation 3 can be applied to sub-grains. For a typical (sub-) grain size distribution where largest (sub-) grains are smaller than twice the average size, the critical particle size, determined by equations 3 and 4, for the two extreme particle repartitions give the following unpinning conditions (6): $d \rangle 3fDm$ for homogeneous precipitation and $d \rangle (2f)^{1/2}Dm$ for (sub-) grain precipitation. The results, for various grain sizes, are shown on Fig. 5: for example an average sub-grain size distribution of .5 µm will be pinned by particles (AlN) precipitating at the subgrain-boundaries until the particle mean size grows to approximately 150Å. Recrystallization follows unpinning and AlN precipitation continues; but inside the new grains the repartition of the precipitates becomes more homogeneous. Some authors reported that the diameter growth of AlN particles is of the $(time)^{1/2}$ form during precipitation (11) and of the $(time)^{1/3}$ form during coalescence (12).

Various authors (13,14,15) observed larger AlN sizes for increasing Al contents. Also, increasing the level of N increases the precipitated volume fraction, f: $f=N_v\pi d^3/6$, where N_v is the number of particles per unit volume. The AlN growth during precipitation, for the four steels tested, can be schematically represented as shown in Fig.6 (15,8). The grain diameter, D_R, theoretically reached at the end of recrystallization decreases with increasing cold reduction (increasing recrystallization nucleation rate). The D_R values, $D_R(R=40\%) \rangle D_R(R=70\%)$ as shown in Fig. 6, can explain, as follows, the four previously mentionned observations obtained from the results.

Observation 1 (Tb=560°C): as shown in Fig.6, the D_R (40%) value being above the precipitation particle diameter curves for the .04%Al steels, grain boundary pinning occurs before completion of recrystallization and probably before the end of AlN precipitation . This pinning will cease after particle coalescence takes place. When R=70%, the value of D_R (70%) is low enough to allow recrystallization to be completed before the average grain size, Dm, reaches the critical size, Dc, defined by the average AlN size, d. For .06% Al steels and R=40%, pinning during recrystallization can still take place but to a lesser degree, since the AlN size is larger and recrystallization is completed for $P_Q=10.8\ K^{-1}$.

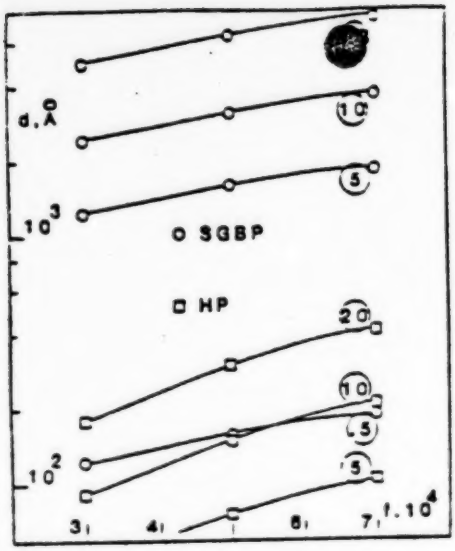

Fig. 5 Critical AlN diameter, d(A), for homogenous, H.P., or (sub) boundary, S.G.B.P., precipitation, versus precipitated volume fraction, f: effect of (sub) grain size (Dc) (μm)

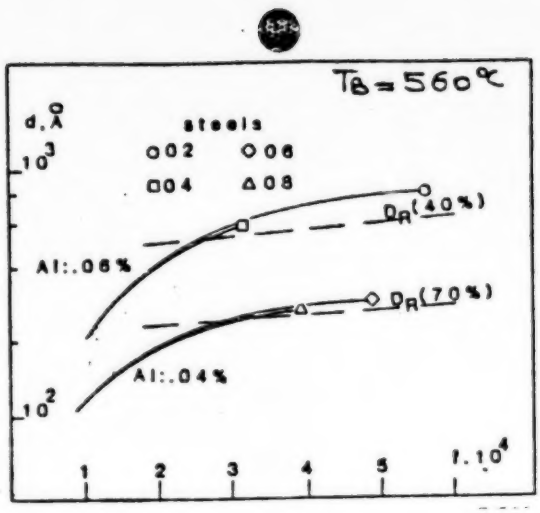

Fig. 6 AlN precipitate diameter, d, versus precipitated volume grain fraction, f.

Observation 1 (Tb=700°C): Fig.6 predicts the possibility of a recrystallization delay, but, since D_R(40%), decreases with the presence of larger carbide particles (16,17,18) and as AlN precipitation is already completed, AlN interactions with grain boundaries should present a lower intensity drag-like effect as compared with grain boundary pinning by precipitation when Tb=560°C. Accordingly, Fig. 3 shows a smaller deviation for P_Q=10.7 when Tb=700°C.

Observation 2 (Tb=560°C): Higher carbon contents tend to produce larger carbide particles which increases the nucleation rate (16,17,18). As a consequence, the grain size at the end of recrystallization decreases.

Observation 3 (Tb=700°C): Fig. 6, as modified for Tb=700°C (D_R curves are lower), shows that the recrystallization size, D_R(40%), is closer to the critical size, Dc (f), than D_R(70%). Grain growth regulated by coalescence kinetics should occur sooner when the cold reduction level is lowered from 70 to 40%. An evaluation of the grain boundary velocities from the values of the slopes $\Delta Sy/\Delta P_Q$ which are approximately 7 Mpa.K for R=40% and 24 MPa.K for R=70%, suggests that grain boundary motion is more affected by AlN particles when R=40% than when R=70%.

Observation 4 (Tb=700°C): The carbide phase is responsible for the yield stress variations (16,17,18). As the carbide phase is usually coarser when formed at higher temperatures, the effect on nucleation rate is stronger when Tb=700°C.

CONCLUSIONS

A simple model, based on the Hillert-Zener theories on grain growth with second phase particles and a thermal parameter calculated with an average activation energy of 60 kcal. $mole^{-1}$, can be used to predict the recrystallization behaviour of aluminium killed steel sheets and the yield stress value after annealing. Important recrystallization delaying effects, resulting in lower formability, can be predicted for low aluminium (.04% Al) steel, coiled at low temperatures (560°C), using low levels of reduction (40%). The same anomaly, though of a lesser degree, can occur with the same .04% Al steels coiled at high temperatures (700°C). The furnace holding times or the cold reduction levels should be carefully chosen in order to avoid the recrystallization delay occuring at low aluminium levels (.04%), resulting in unacceptable large variations of yield stress values.

This model allows in practice a better adjustment of furnace holding times which will result in energy savings and better control over the quality of the final product.

Acknowledgement

The authors whish to thank Dr. H. LeHuy (IMRI) for helpfull discussions, D. Simard (IMRI) for his technical assistance and Dr. A. Crawley (CANMET) for his contribution in the cold rolling.

References

1- W.B. Hutchinson, Int. Met. Rev., 1984, vol 29,n°1.
2- J.L. Lebrun, G. Maeder, F. Moliexe and P. Parnière, Commission des Communautés Européennes, rapport final n° EUR 6652 FR, 1980.
3- I.L. Dillamore, W.B. Hutchinson, Trans. ISIJ, n°11, 1971.
4- W. Jolley, Trans. ASM, vol. 3, Jan. 1972, 245.
5- P.L. Aubrun et P. Rocquet, Mem. Sci. Rev. Metall., n°4, 1973.
6- Y. Meyzaud, P. Parnière et B.J. Thomas, Mém. Sci. Rev. Métall. Avril 1978.
7- R.L. Rickett, S.H. Kalin, J.I. Mackenzie, met. Trans., march 1949 p. 242-251.
8- Y. Meyzaud, B. Michaud and P. Parnière, Texture and the properties of materials, conf. published by Metals Society n°178, 1976, 255-265.
9- M. Hillert, Acta Met. vol.13, March 1965, 227.
10- Ch. Hénin and Ch. Brun, Rev Mét. CIT, Juillet 1981.
11- E.I. Brown and E.J. Deardo, Conf. thermomechanical procession ofmicroalloyed austenite, Pittsburgh, 17-19 Aug. 1982, 319-341, Met. Soc. AIME.
12- A.J. Ardell, Acta Met., vol. 20, Jan. 1972, p.61.
13- Y. Yagi, T. Fukutsuka and R. Ogawa, Trans. ISIJ, 12, 1972, p.233-240.
14- H. Berns, Stahl und Eisen, June 29th 1978, 98, n°13, p.662-664.
15- H.S. Choi, C.M. Lee and J. Choi, Journ. Korean Institute of metals, vol.16, 6, 1978, p.485-94.
16- K. Onel and J. Nutting, Mat. Sci., March 1981.
17- T. Gladman, I.D. Mc Ivor and F.B. Pickering, J.I.S.I., may 1971.
18- E. Nes and J.A. Wert,, Scripta Met., vol.18, p. 1433-1438, 1984.